CLFV in Heavy States

Workshop Summary

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for EF09

Oct 2nd 2020

Workshop Agenda

10:00 AM	→ 10:10 AM	**Welcome** Speaker: Bertrand Echenard (Caltech) Workshop-heavy-int...
10:10 AM	→ 10:40 AM	**(Theoretical) Introduction to heavy state LFV decays** Speaker: Wolfgang Altmannshofer (UC Santa Cruz) altmannshofer_LFV...
10:40 AM	→ 11:10 AM	**Experimental review of Higgs LFV decays** Speaker: Cecile Caillol LHCwkspCaillol.pdf
11:10 AM	→ 11:40 AM	**Experimental review of Z,W,t LFV decays** Speaker: Stefania Xella (Niels Bohr Institute, Denmark) Presentation-Xella-...
11:40 AM	→ 12:00 PM	Coffee break
12:00 PM	→ 12:30 PM	**Theory of LFV in exotic decays** Speaker: Yongchao Zhang exotic_LFV.pdf
12:30 PM	→ 1:00 PM	**Experimental review of LFV in exotic decays** Speaker: Dr Mukherjee Swagata (RWTH Aachen) LFV_snowmass.pdf
1:00 PM	→ 1:30 PM	**Open discussion**

CLFV - Heavy state decays

Thursday Sep 3, 2020, 10:00 AM → 2:25 PM US/Central

- Joint workshop EF02-EF09-RF5
  https://indico.fnal.gov/event/44931/
- Review constraints on direct searches of charged lepton-flavor violation decays of heavy (W,Z,t,H, heavy exotic) states
- Interplay with low-energy constraints
- Huge thanks to the speakers and attendees
  - This summary borrows/summarizes slides presented. All credits to workshop's speakers, all mistakes/omissions on me

Heavy SM State LFV Decays and New Physics

- In the SM, LFV decays of Z, Higgs and top heavily suppressed

$$\text{e.g.}\quad \mathrm{BR}(Z \to \mu e) \sim \mathrm{BR}(Z \to \mu\mu) \left| \frac{g^2}{16\pi^2} \frac{m_\nu^2}{m_W^2} \right|^2 \sim 10^{-50}$$

- New Physics at a scale Λ_{NP} alters these BRs

$$\frac{\mathrm{BR}(Z \to \mu e)}{\mathrm{BR}(Z \to \mu\mu)} \sim g_{NP}^2 \left(\frac{v}{\Lambda_{NP}} \right)^4 , \qquad \frac{\mathrm{BR}(H \to \tau\mu)}{\mathrm{BR}(H \to \tau\tau)} \sim g_{NP}^2 \left(\frac{v}{\Lambda_{NP}} \right)^4$$

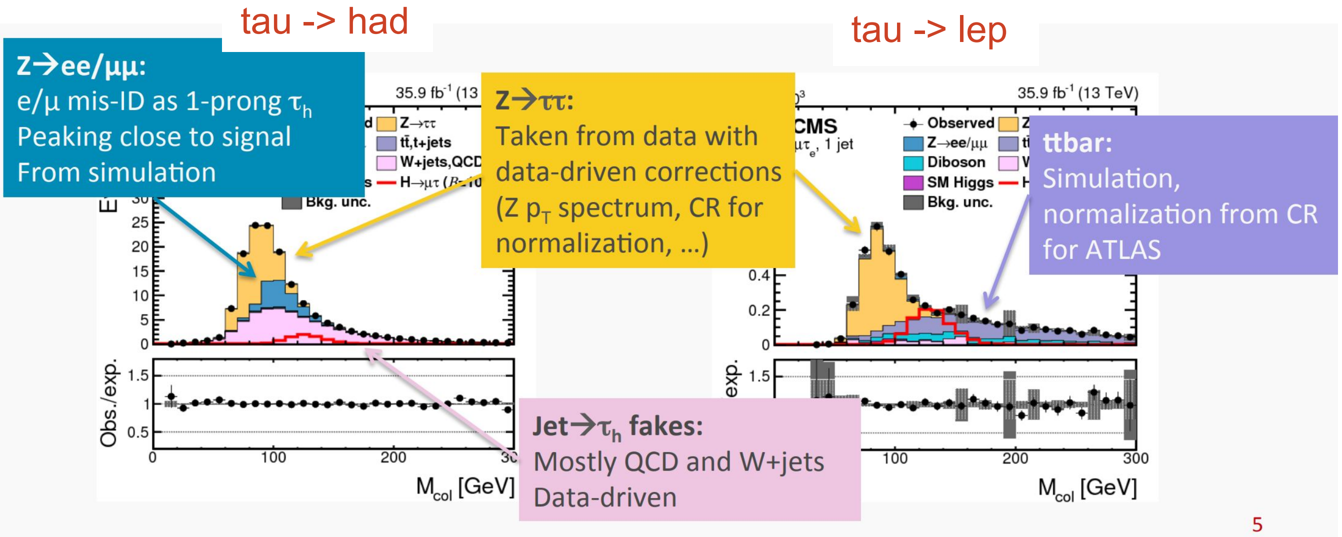
$$\frac{\mathrm{BR}(t \to c\mu e)}{\mathrm{BR}(t \to Wb)} \sim \frac{g_{NP}^2}{16\pi^2} \left(\frac{v}{\Lambda_{NP}} \right)^4$$

- Caveat: the situation in concrete model can be quite different

LFV in Higgs decays

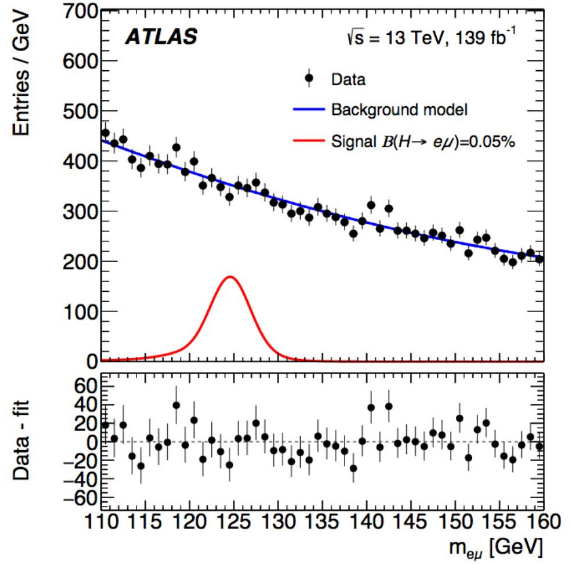
- Searches limited by statistics of available Higgs bosons and large backgrounds
  - Further categorize events based on expected Higgs production mechanism

H -> e/μ τ

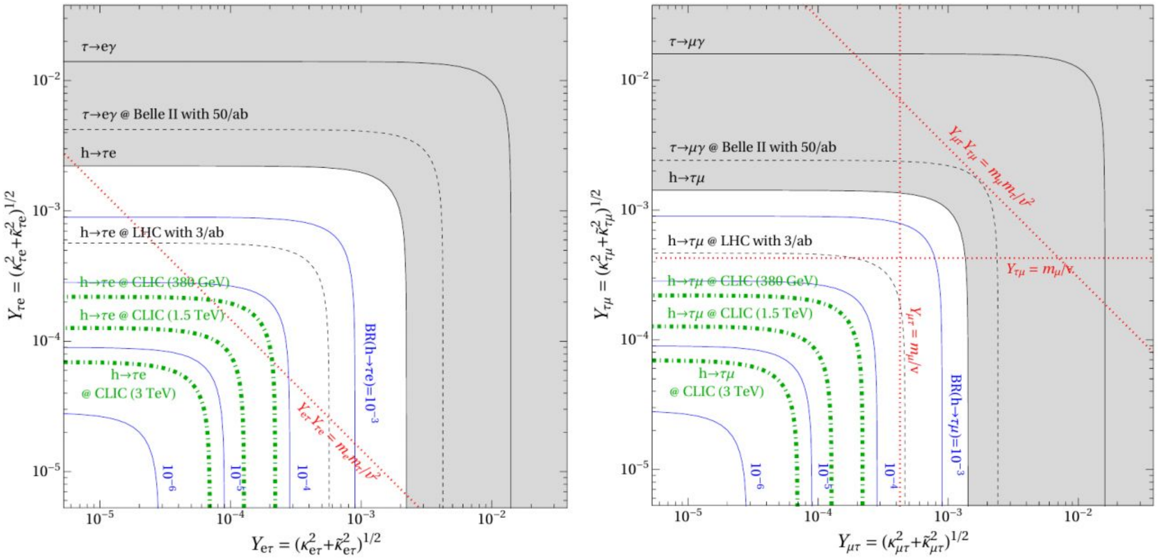


H -> eμ

arXiv:1909.10235



LFV in Higgs decays



- Weak indirect constraints from $\tau \to \mu\gamma$ and $\tau \to e\gamma$.
- But $\mu \to e\gamma$ strongly constrains BR($H \to \mu e$) and BR($H \to \tau\mu$)×BR($H \to \tau e$)

Blankenburg, Ellis, Isidori 1107.1216; Harnik, Kopp, Zupan 1209.1397; Davidson, Verdier 1211.1248

LFV in Z decays and high-mass di-lepton

Run 1+2+3 :
300 fb^{-1}

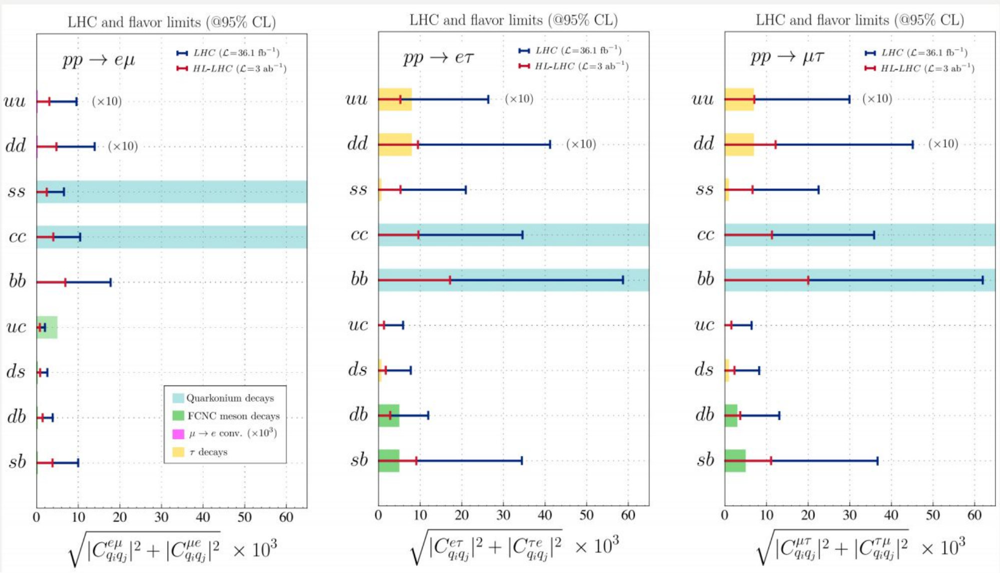
1.5 10^{10} Z's
6 10^{10} W's
2 10^{8} top's

End of HL-LHC :
3000 fb^{-1}

Take advantage of large number of produced W,Z and top at LHC

- Severe indirect constraints on $Z \to \mu e$ from $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion (barring accidental cancellations).
  (e.g. Delepine, Vissani hep-ph/0106287; Davidson, Lacroix, Verdier 1207.4894)

- Complementary sensitivity in the case of taus.

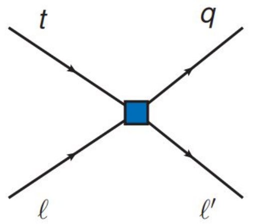


High mass di-lepton final state can provide complementary coverage

Eff. coeff.	Operator	SMEFT
$C^{ijkl}_{V_{LL}}$	$\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{Lk}\gamma^\mu \ell_{Ll})$	$\mathcal{O}^{(1)}_{lq}, \mathcal{O}^{(3)}_{lq}$
$C^{ijkl}_{V_{RR}}$	$(\bar{q}_{Ri}\gamma_\mu q_{Rj})(\bar{\ell}_{Rk}\gamma^\mu \ell_{Rl})$	$\mathcal{O}_{ed}, \mathcal{O}_{eu}$
$C^{ijkl}_{V_{LR}}$	$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{Rk}\gamma^\mu \ell_{Rl})$	$\mathcal{O}_{qe}$
$C^{ijkl}_{V_{RL}}$	$(\bar{q}_{Ri}\gamma_\mu q_{Rj})(\bar{\ell}_{Lk}\gamma^\mu \ell_{Ll})$	$\mathcal{O}_{lu}, \mathcal{O}_{ld}$
$C^{ijkl}_{S_R}$	$(\bar{q}_{Ri} q_{Lj})(\bar{\ell}_{Lk} \ell_{Rl}) + \text{h.c.}$	$\mathcal{O}_{ledq}$
$C^{ijkl}_{S_L}$	$(\bar{q}_{Li} q_{Rj})(\bar{\ell}_{Lk} \ell_{Rl}) + \text{h.c.}$	$\mathcal{O}^{(1)}_{lequ}$
C^{ijkl}_{T}	$(\bar{q}_{Li}\sigma_{\mu\nu} q_{Rj})(\bar{\ell}_{Lk}\sigma^{\mu\nu} \ell_{Rl}) + \text{h.c.}$	$\mathcal{O}^{(3)}_{lequ}$

LFV in top decays

Take advantage of large number of produced W,Z and top at LHC



3 body decays that violate lepton and quark flavor $t \to q\ell\ell'$

(Davidson, Mangano, Perries, Sordini 1507.07163)

The decays are competing with an unsuppressed 2 body decay $t \to Wb$

$$\mathrm{BR}(t \to c\mu e) \sim \frac{g_{\mathrm{NP}}^2}{16\pi^2}\left(\frac{v}{\Lambda_{\mathrm{NP}}}\right)^4 \sim 2 \times 10^{-5} \times g_{\mathrm{NP}}^2 \left(\frac{1\ \mathrm{TeV}}{\Lambda_{\mathrm{NP}}}\right)^4$$

- ▶ Possibly in reach of the LHC for New Physics at the TeV scale.

80 fb^{-1} 13 TeV

$\mathcal{B}(t \to \ell\ell' q) < 1.36^{+0.61}_{-0.37} \times 10^{-5}$ (expected).

[11]

$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5}$ (observed).

$\mathcal{B}(t \to e\mu q) < 4.8^{+2.1}_{-1.4} \times 10^{-6}$ (no τ in cLFV vertex, expected),

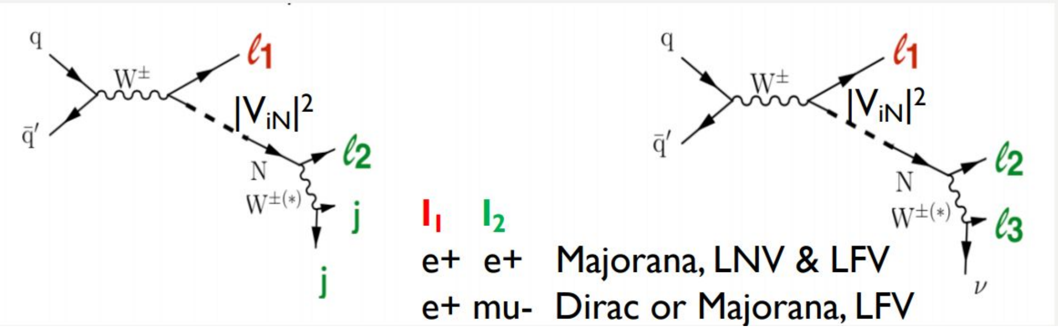
$\mathcal{B}(t \to e\mu q) < 6.6 \times 10^{-6}$ (no τ in cLFV vertex, observed).

Very few studies available for HL-LHC

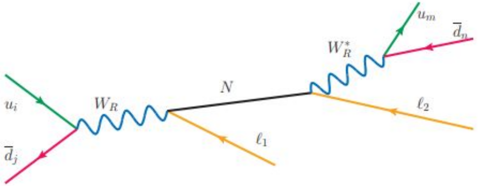
Table 5 Expected upper limits on $BR(t \to q\mu^{\pm}e^{\mp})$, under the hypothesis of the absence of signal, for 8, 13 TeV (in two scenarios: the case of 20 and 100 fb^{-1} collected luminosity) and 14 TeV for 3000 fb^{-1} collected luminosity

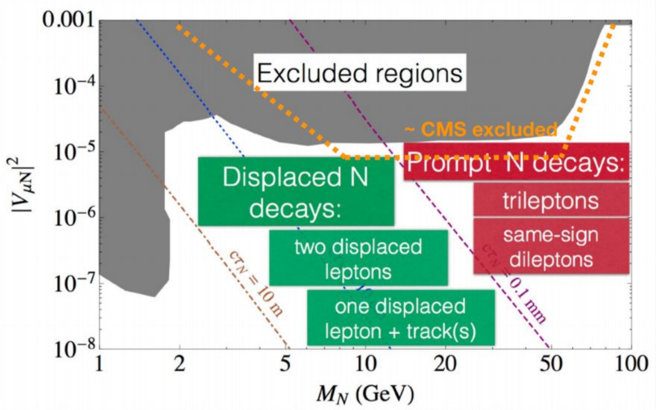
	8 TeV (20 fb^{-1})	13 TeV (20 fb^{-1})	13 TeV (100 fb^{-1})	14 TeV (3000 fb^{-1})
$BR(t \to q\mu^{\pm}e^{\mp})$	$<6.3 \times 10^{-5}$	$<2.9 \times 10^{-5}$	$<1.2 \times 10^{-5}$	$\lesssim 2 \times 10^{-6}$

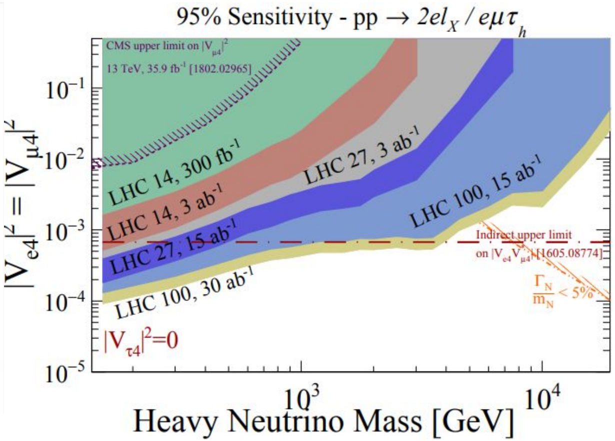
LFV/LNV in W and high-mass W_R decays

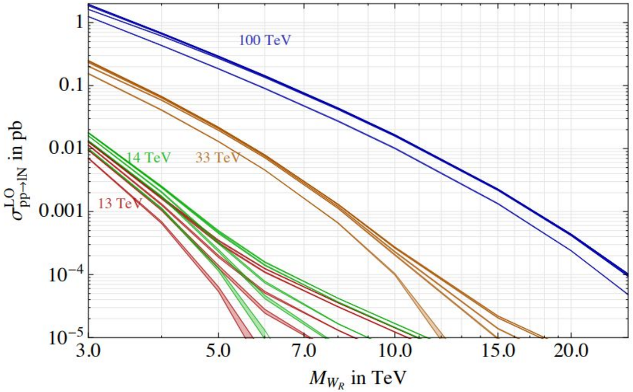


Extrapolations show up to $m(W_R)$ ~ 35 TeV for 100 TeV pp collider, depending largely on RHN mass for $l_1 l_2 jj$





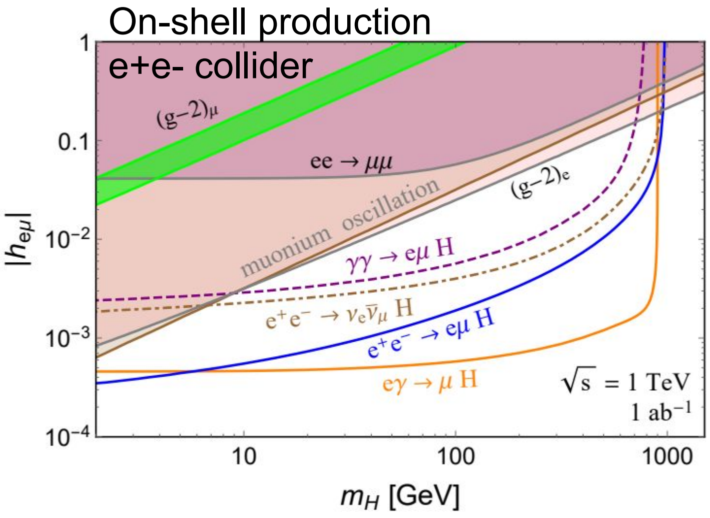




Direct searches for LFV decays in exotic states

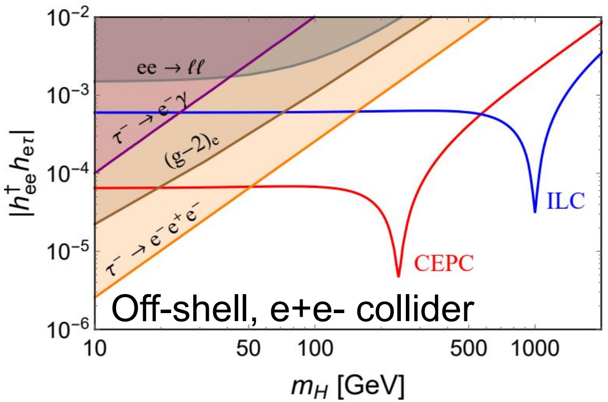
Heavy resonances appear in most BSM models

Interplay with low-energy searches can heavily depend on model, but some of these searches are complementary, some largely constrained



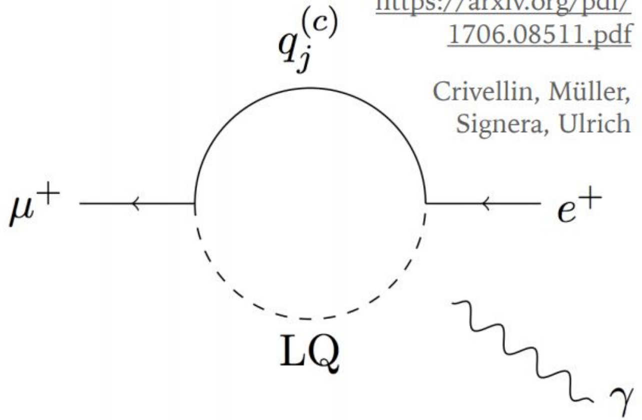
LHC searches

Final state	Interpretations	Dataset	Experiment
eμ	RPV, QBH, Z'	36/fb, 13 TeV	CMS
eτ, μτ	RPV, QBH, Z'	36/fb, 13 TeV	ATLAS
Multileption	Heavy fermions	36/fb, 13 TeV	CMS
μτ	Light scalar	2/fb, 13 TeV	LHCb
μτ	Heavy scalar	36/fb, 13 TeV	CMS



Few words about Leptoquarks

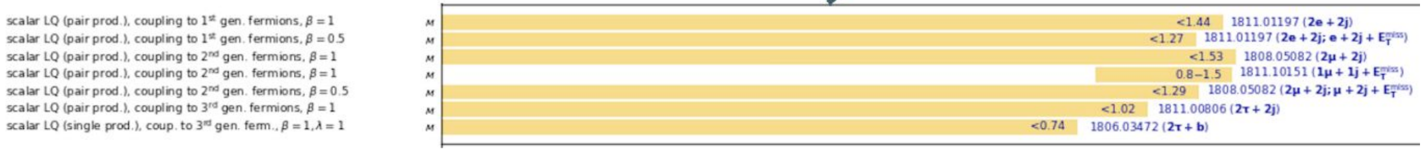
- Leptoquarks could lead to LFV and LFUV
- Increased interest in leptoquark searches due to B-anomalies
- LQ LFV models generally have very low cross-section, or allowed LQ mass very high, so current searches focus on generation specific LQs
- Pair production/ single production
- Mass exclusion limit at the ballpark of 1 TeV (depends on model)



https://arxiv.org/pdf/1706.08511.pdf

Crivellin, Müller, Signera, Ulrich

Summary of CMS LQ searches



Conclusions

- Productive workshop to explore connections between energy frontier and RF5
- Interplay with low-energy measurements results in some complementarity

- Very few projection for HL-LHC
  - Some of the analyses are rather complicated, such that a simple extrapolation is unlikely to yield an accurate estimation of the HL-LHC sensitivity

- Some exploration of future collider reach available
  - not comprehensive by any means

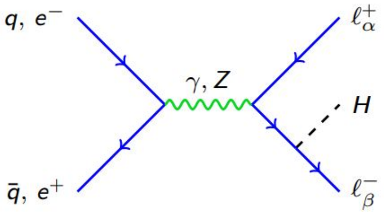
BACKUP

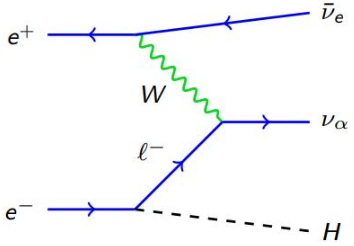
On-shell production of H at hadron/lepton colliders

Dev, Mohapatra & YCZ '18 PRL; PRD

- the $q\bar{q}/e^+e^-$ process

$$q\bar{q},\, e^+e^- \to \ell_\alpha^\pm \ell_\beta^\mp + H\,, \quad e^+e^- \to \nu_\alpha \bar{\nu}_e + H$$





- involving the laser photon(s)

$$e^\pm\gamma \to \ell^\pm + H\,, \quad \gamma\gamma \to \ell_\alpha^\pm \ell_\beta^\mp + H$$